



# OPTIMUM DESIGN OF CONTINUOUS PLATE GIRDER WITH VARIABLE DEPTH

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## ABSTRACT

*The need to protect our global environment, and to decrease the amount of embodied air emissions (carbon, sulphur and nitrogen oxides) for new steel structures, has called for the effective use of steel in construction. These besides the importance of plate girders in structural engineering for upholding high significance structures necessitate the must to find the best plate girder design in terms of both performance and economy. These can be accomplished by design optimisation. Hence, this work deals with the optimum design of continuous plate girder with variable depths.*

*A nonlinear optimisation technique relied upon a Generalised Reduced Gradient method, embedded in Microsoft Excel Solver was utilised to find the minimum weight of continuous plate girder. This was achieved by finding the optimum web depth, span length and area of the continuous steel girder satisfying the ultimate and serviceability limit state requirements of BS 5950-1:2000 for different loads. A formulated optimisation procedure was applied in a case study in order to evaluate the efficiency of the proposed structural design formulation.*

*The study results demonstrated that an increase in web plate depth translates to reduction in the girder cross sectional area, and by inference decrease in the girder weight. It was excitingly found that optimisation of continuous plate girder design can be more economical with a benefit of 18.81% reduction in the weight compared to the conventional design.*

*This clearly illustrates the exciting promises of optimisation in continuous plate girder design. The study produces various design charts that can be utilized by structural engineers when designing long span buildings. Recommendations for future investigations were suggested.*

**Key words:** Optimisation, Continuous plate girder, Variable depth, Generalised Reduced Gradient (GRG), Excel solver and BS5950-1:2000.

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## 1. INTRODUCTION

The ability of the plate girder to withstand the transmitted imposed loads from large structures through the web plates depends on the design of the plate girder. Meanwhile, high depths are required to withstand such massive loads [1]. In addition to technical factors that must be considered in the design of plate girders (variations in plate sizes and section properties). Another significant factor is economic factor, which is the object of the design. According to Khorasani et al [2], the cost of plate girders is often influenced by their weight. Interestingly, a recent investigation performed by Limaye and Alandkar [3], showed that “Tapered (varying depth) web is one of the new technique proposed in design in order to achieve economy and to reduce its self-weight.”. Additionally, a study conducted by Culmo [4], revealed that “Continuous-girder spans require less structural steel and fewer bearings”. Thus, the present study is very important and will make a great contribution to the understanding of tapered continuous plate girders regarding their benefit in maximising the bearing strength, durability as well as achieving the quest of minimum weight at satisfactory performance, using optimum design.

“Optimisation is a technique established by engineers to design and generate products and structures both economically and efficiently. To apply optimisation, different methods have been developed to manage variety of problems [5], including Generalised Reduced Gradient (GRG), Sequential Quadratic Programming (SQP) and Genetic Algorithms (GA). Also, different tools have been used to apply these methods, such as Microsoft Excel Solver and matrix laboratory (MATLAB)” [6]

According to Lee et al [7], the GRG method has been proven as one of the robust, accurate, precise and effective methods for the non-linear Programming problems. Ozgur [8] revealed that it is due to GRG efficiency that GA method is directly applicable to unconstrained problems. The GRG method was adopted in this work because the optimisation of the continuous plate girders is a constrained nonlinear problem. Nevertheless, since the use of GA method requires penalty function methods, which is the key difficulty of the design, the optimum design of the continuous plate girders was carried out with GRG method instead of the GA. Furthermore, Excel solver which is an add-in for Microsoft Office was used as an optimisation tool due to its availability.

Codes of practice consist of standards and regulations compiled by proficient engineers and official authorities, upon which structural engineers rely on to design various engineering structures. They provide practical guidance, safety and serviceability in structural design. Similarly, to any other structural element, there are various codes of practice for designing of continuous plate girders depending on the region. The present study relied on the provision of BS 5950-1:2000 (Code of practice for steelwork in building: design of rolled and welded sections) which is considered as a valuable tool to deliver more quality, safety and sustainability process.

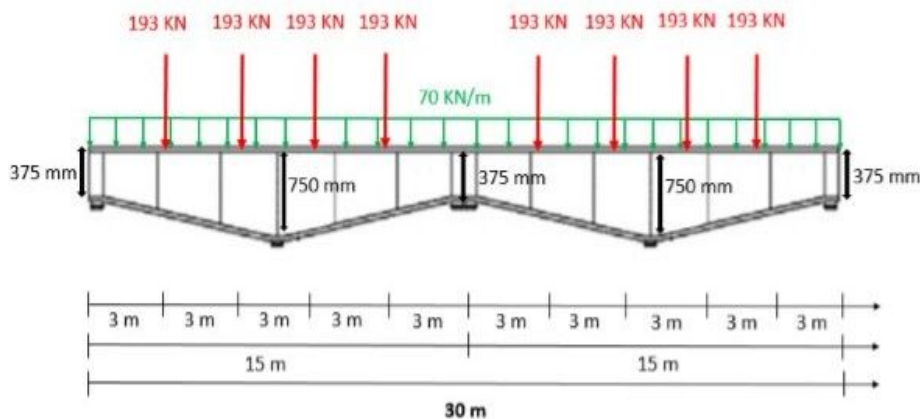
The aim of this research is to determine the optimum design of continuous plate girders with variable depth in relations with minimum weight using BS 5950-1:2000. In order to accomplish the desired goal of this investigation, the objectives is to:

- To study the optimum design of continuous plate girders and formulate the objective function, design constraints, variables and parameters with respect to BS 5950-1:2000 and by using the tool of GRG method in the Microsoft Excel Solver.
- Investigate and evaluate the impact of different (depth/ weight/ loads) ratios of steel on the performance of the optimum design technique concerning the minimum (weight/cost).
- To examine and compare the results acquired from convectional design with the results of the optimisation process.

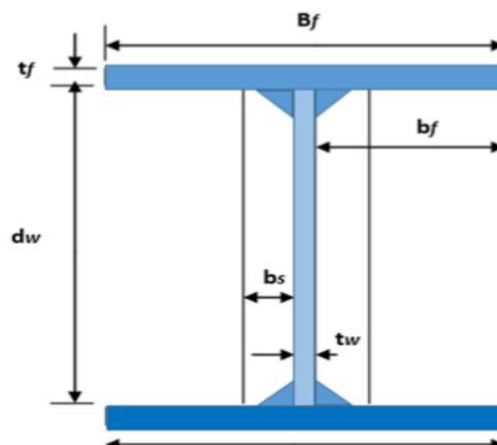
- To elaborate an optimum design charts that can be adopted in designing continuous plate girders according to BS 5950-1:2000

## 2. METHODOLOGY

The study considered design of continuous steel plate girders to carry different factored loads. The weight of these girders was taken as the volume of the steel required multiplied by the density of steel. Meanwhile, the weight of welds was considered negligible. A clear explanation was presented in the following sections. Beginning from the conventional design equations which are presented in one formula on the excel spreadsheet with the aim to minimise the weight of the steel. This will be followed by details regarding the optimum design formula using BS 5950-1:2000. In particular cases, deep flexural members are used instead of rolled sections due to their ability to economically carry heavy loads and very large spans. In the plate girder section, it is the deep web plate that resists to shear forces and the flanges (top and bottom) that resist to bending moments. In order to have an efficient cross section in resisting in plane bending, it is necessary to place the maximum material far away from the neutral axis. For this reason, it is economical to place the flange plates as far apart as possible. The depth of the plate girder increases, as the axial force in the flange plates diminish. In such a case, premature failure of plate girder due to web plate buckling in shear may occur. As long as structural efficiency is particularly concerned, tapered (non-prismatic) with continuous variable cross sections are studied.



**Figure 1** Loading of the tapered continuous plate girder

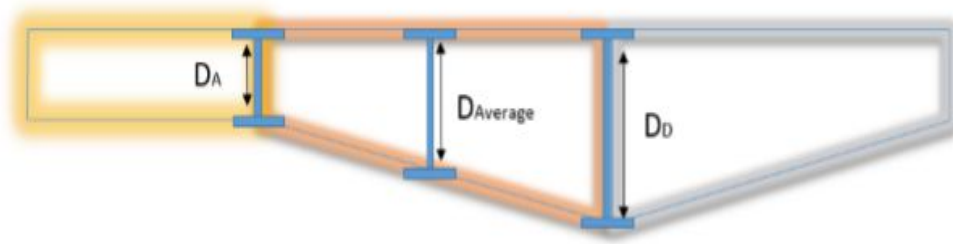


**Figure 2** Plate Girder Section

## 2.1. Assumptions

- The continuous plate girder has a non-uniform cross section through its length
- The web and flange plates were made from the same homogenous material
- No longitudinal stiffeners used
- Transfer stiffeners are used only where obligatory

## 2.3. Objective Function



**Figure 3** Different sections of the continuous plate girder

The objective function was minimize based on the code/design constraints below

$$Z = 2L \times [\{D_A \times 0.8L\}_{Rectangle Area} + 2\{D_D + D_A \times 0.2l\}_{Trapezoid Area} + \{2B_f t_f + d_w t_w\}_{section A} + \{2b_f t_f + d_w t_w\}_{section D} + \{2b_f t_f + d_w t_w\}_{Average} + \{2t_s d_s d_w\}_{stiffener}]$$

## 2.4. Design Explanation

### 2.4.1. Dimension of the Plate Girder

According to the clause 4.4.3.2 from the British standers BS-1:2000, the minimum web plate thickness is as follows:

$$t_w \geq \frac{d}{250} \quad (1)$$

$$t_w \geq \left(\frac{d}{250}\right) \left(\frac{P_y f}{P_y}\right) \quad (2)$$

Since the Grade 50 steel 355 is used,

$$t_w \geq \left(\frac{d}{250}\right) \left(\frac{P_y f}{355}\right)$$

Where,

$P_y f$ : is the compression strength of the flange

$P_y$ : is the uniform stress of the flanges

According to Owens [9] and Davison et al [10] the recommended span/depth ratio for continuous steel girders varies between 15 for short span girders and 25 for long span girders.

$$\frac{L}{25} \leq d \leq \frac{L}{15} \quad (3)$$

Where,

$L$ : is the length of the girder

### 2.4.2. Section Classification and Proportional Limitation

#### Flange

Flange is supposed at least compact since only the flange that will resist the moment. Therefore, the outstand element of compression flange based on table 11 from BS-1:2000 code is;

$$b_f t_f > 13 \epsilon \quad (4)$$

Where,

$$\epsilon = \sqrt{\frac{275}{P_{yf}}}$$

$$P_{yf} = 275 \quad \text{if} \quad t_f \leq 16 \quad (5)$$

$$P_{yf} = 265 \quad \text{if} \quad 16 \leq t_f \leq 40 \quad (6)$$

$$P_{yf} = 255 \quad \text{if} \quad 40 < t_f \leq 63 \quad (7)$$

$$0.3 d \leq B_f \leq 0.5 d \quad (8)$$

$$B_f = 2 b_f + t_w \quad (9)$$

Where,

$B_f$ : is the width of the flange

#### Web

According to Bradford et al [11] and Owens [9] design guides table 8, the web section needs to be classified based on its ability to reach the yield stress (plastic, compact, slender or semi-compact) and also checked whether it is prone to shear buckling. Therefore, with the neutral axis at mid-span; the web section in the present study was semi compact and susceptible to shear buckling

$$\frac{d_w}{t_w} \leq 120 \epsilon \quad \text{Web semi - compact} \quad (10)$$

$$\frac{d_w}{t_w} > 63 \epsilon \quad \text{Web prone to shear buckling} \quad (11)$$

Where,

$$\epsilon = \sqrt{\frac{275}{P_{yf}}} \quad (12)$$

### 2.4.3. Moment Resistance

Based on (cl. 4.2.5 BSI 2000), (cl. 4.3.7.3 BS5950:Part1) and (cl 2.3.2 BS 5950: Part 3.1) design requirements, lateral torsional buckling has to be checked and compared to the flange moment capacity and the lesser of these two values is the design capacity.

$$M_b > M_u \quad \text{To check lateral torsional buckling} \quad (13)$$

$$M_b = S_x P_b \quad (14)$$

Where,

$M_u$ : Actual factored bending moment at mid-spans (maximum)

$M_b$ : Buckling resistance moment

$P_b$ : Bending strength for welded sections

$S_x$ : Plastic section modulus of the cross section

$$M_c > M_u \quad \text{To check moment capacity for flanges only} \quad (15)$$

Where,

$$M_c = P_{yf} A_f d \quad (16)$$

$$d = d_w + t_f \quad (17)$$

$$S_x = \frac{M_p}{F_y} \quad (18)$$

$$M_p = 2 F_F y_F + 2 F_w y_w \quad (19)$$

$$y_F = \frac{D}{2} - \frac{t_f}{2} \quad (20)$$

$$y_w = \left[ \frac{(D-2t_f)}{2} \right] \frac{1}{2} \quad (21)$$

$$F_F = A_f F_y \quad (22)$$

$$F_w = \left( \frac{A_w}{2} \right) F_y \quad (23)$$

Where,

$d$ : Distance between centroid of flanges

$A_f$ : Flange area

$A_w$ : Web area

$M_p$ : Plastic moment of resistance in torsion

$F_y$ : Steel yield limit

$y_F$ : Distance from the centroid of the flange to the neutral axis of the I-section

$y_w$ : Distance between the neutral axis of the I-section and the web height

$F_F$ : Yield stress of flange

$F_w$ : Yield stress of web

$t_f$ : Thickness of flanges

$D$ : Total height of the I-section

#### 2.4.4. Shear Capacity without Tension Field Action

In order to calculate shear buckling resistance of thin webs, the clause 4.4 of BS 5950: Part1 was applied. This clause relates to webs which are supposed to carry shear only. Further more, webs without intermediate stiffeners must be designed in accordance with the clause 4.4.5.3 of BS 5950. However, this clause may be employed conservatively if stiffeners are present. At this early stage of design it is not known if stiffeners will be needed. However, as point loads are included they might be required for local web buckling. Therefore, the clause 4.4.5.3 regarding design without the use of tension field action will be employed. This has the benefit of simplifying calculations even though stiffeners are shown to be needed later on. According to BS 5950: Part 3.1 clause 4.1.4 requirement, it would be prudent to do this check early on as the total vertical shear will be supported by the web. In this study, these checks for shear buckling resistance will be in different positions (A, S and D) of the continuous steel plate girder since it has a non-uniform section.

$$V_{cr} > F_v \quad (24)$$

$$\frac{d_w}{t_w} < 63 \epsilon \quad (25)$$

$$P_v > F_v \quad (26)$$

Where,

$$P_v = 0.6 P_y A_v \quad (27)$$

$$A_v = t_w d_w \quad (28)$$

$$\epsilon = \sqrt{\frac{275}{P_{yf}}} \quad (29)$$

$$V_{cr} = q_{cr} d_w t_w \quad (30)$$

Where,

$P_v$ : Web shear capacity

$A_v$ : Shear area

$P_{yf}$ : Design strength of the flange

$\epsilon$ : Strain of steel

$d_w$ : Web height

$t_w$ : Web thickness

$V_{cr}$ : Critical shear buckling resistance

$q_{cr}$ : Shear buckling resistance

$F_v$ : Maximum shear force

#### 2.4.5. Stiffeners Check

Based on clause 4.5.1.2 from BSI: 2000 code, the maximum outstand of web a stiffener is;

$$b_s \leq 13 t_s \epsilon \quad (31)$$

Moreover, the spacing according to (clause 4.4.3 BSI 2000) is;

$$a > 1.5 d \quad (32)$$

Additionally, the minimum stiffness according to (clause 4.4.6.4 BSI 2000) is;

$$I > I_s \quad (33)$$

Where,

$$I_s = 0.75 d_w t_w^3 \text{ min}$$

$$I = \frac{t_s(2b_s + t)^3}{12}$$

In order to check the bearing and buckling resistance of stiffeners, the following formula will be considered;

$$P_x > F_x \quad (34)$$

$$\frac{0.8 F_x}{P_{ys}} < A_s \quad (35)$$

Where,

$$P_x = P_y A_s$$

$P_x$ : Buckling resistance of the stiffener

$F_x$ : Factored external load or reaction

$A_s$ : Stiffener area

$P_y$ : Uniform stress

$P_{ys}$ : Compression strength of the stiffener

### 3. RESULTS

#### 3.1. Minimum Weight from Volume Optimisation

The optimisation using Excel solver showed an 18.81% reduction in the total cross-sectional area of the continuous tapered plate girder. Since the elements were assumed to be made from the same homogenous steel, this will also interpret into 18.81% reduction in weight. In real life design, though the width of flanges may not be subject to space constraint, the girder depth is often an issue in structures. Broadly speaking, in all industrial and residential designs, the headroom is of great importance. This explains the implementation of various depths in this optimisation process. As shown in Figure 4 below, it was observed that the decrease in the web depth ( $d_w$ ) of the plate girder caused an increase in the flange plate thickness ( $t_f$ ). This is reasonable since the moment capacity is reliant on both depth and flange area of the girder. According to the method of “flange only”, the moment resisting capacity is the product of lever arm (depth of girder) and the flange area.

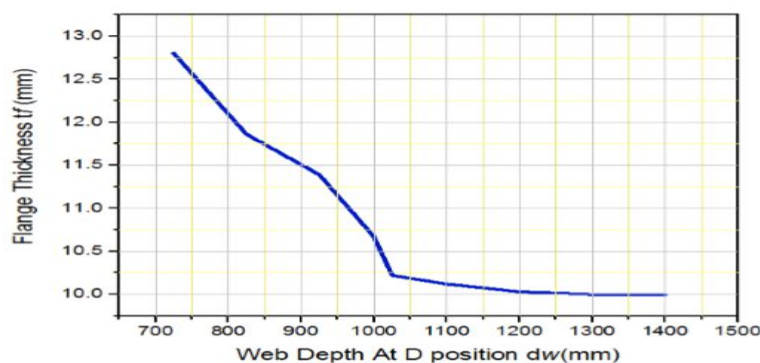


Figure 4 Relationship between the flange thickness and the web depth

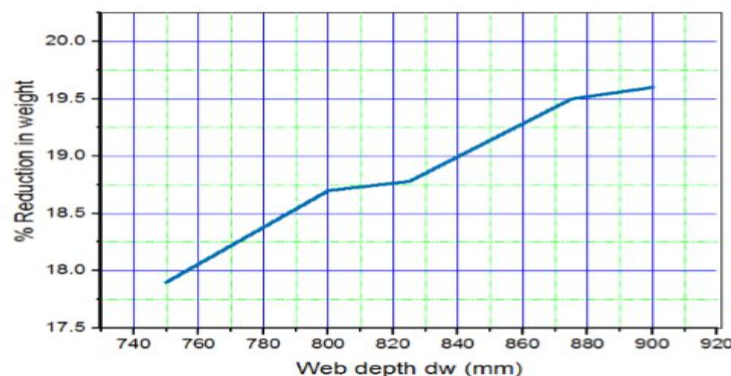


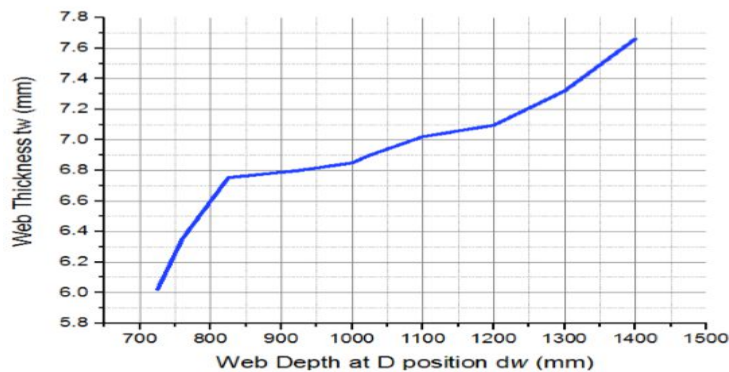
Figure 5 Relationship between the web depth and the percentage reduction in weight

The two-line graphs above Figure 5 depict the relation between flange plates thickness and web depth and the relation between web depth and the percentage reduction in weight. They clearly show that increase in web plate depth translates to reduction in the girder cross sectional area, and by inference decrease in the girder weight. This indicates that deep girders are more economical and can be effectively used over intermediate supports (tapered girders) in order to save weight in midspan regions. However, because of headroom constraint and web buckling susceptibility, the girder depth cannot be increased infinitely.

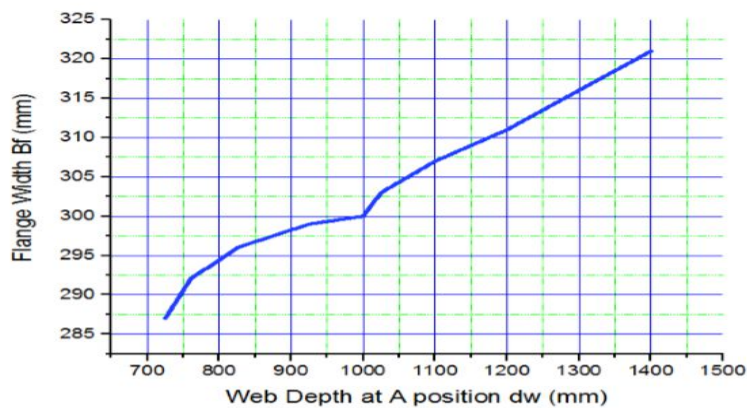
The two-line graphs above Figure 6, 7 present the relation between the web thickness and the web depth in two locations since it is a non-uniform continuous girder. However, both graphs indicate a slight increase in web thickness ( $t_w$ ) with increase in girder depth ( $d_w$ ). This



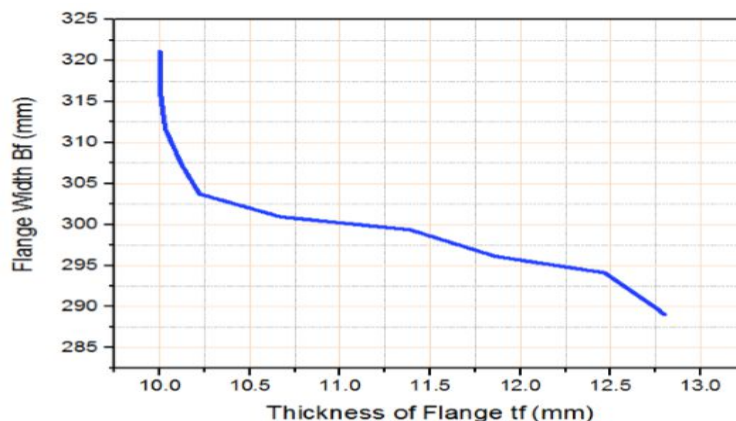
positive relationship was possibly influenced by the code provision, it sustains that web capacity to withstand large shear force and to prevent shear buckling depend largely on the plate thickness as discussed in literature review (section 2.2). Thus, it is important to prevent the occurrence of too slender web for adequate girder strength and stiffness.



**Figure 6** Relationship between the web depth and the web thickness



**Figure 7** Relationship between the web depth and the flange width



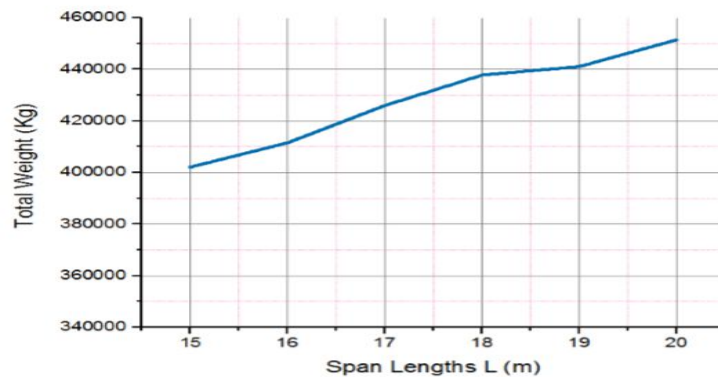
**Figure 8** Relationship between the flange thickness and the flange width

In addition, figure 8 reveals that the flange width ( $B_f$ ) decreases as the thickness of the flange ( $t_f$ ) increases. This is because the moment resistance relies upon the product of these two variables (flange area). Thus, the increase in one results in decreasing the other.

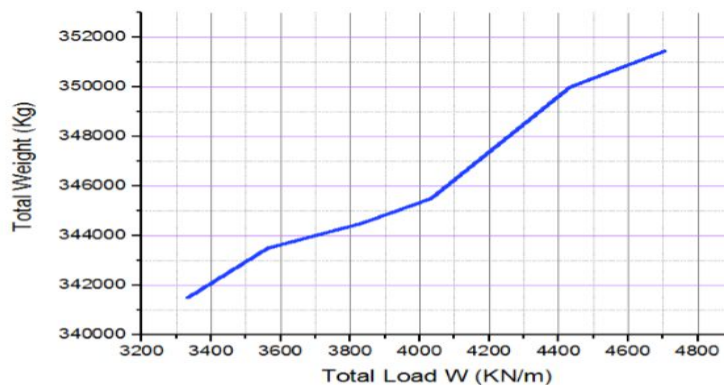
The effect of changing span length parameter on the total weight of the continuous plate girder was also examined. The girder span length was increased in increments of 1m in order to observe its effect on the minimum weight design. The results presented in figure 9 revealed

that total weight of the continuous girder increases gradually and proportionally with the span length. This rise in weight was expected, as more material would be needed while increasing the span length, which often determines the quantity of steel. This also leads to an increase in volume and consequently in weight. On closer inspection of results, the increase in gradient between all the increments can be explained that all constraints are satisfied and altering the dimensions of the variables. Due to an extensive interest for girders usage in construction, this study has examined the dimensions and the effect of changing span lengths so all the needs of design fabrication can be satisfied. This was the case for many recent studies such as [12], [13] and [14] that have also focused on long-span building typology in order to help designers find solutions from a geometrically diverse variety of high performing building forms.

In order to observe the impact of changing the total girder loading on the weight of the continuous plate girder, the total loading was increased in increments of 200 KN/m. The results display that the optimum weight of the continuous plate girder increases steadily by increasing the total imposed load, as shown in figure 10. This increase in weight was predictable as the dimensions of the steel plates variables have to increase in order to support the increasing loadings.



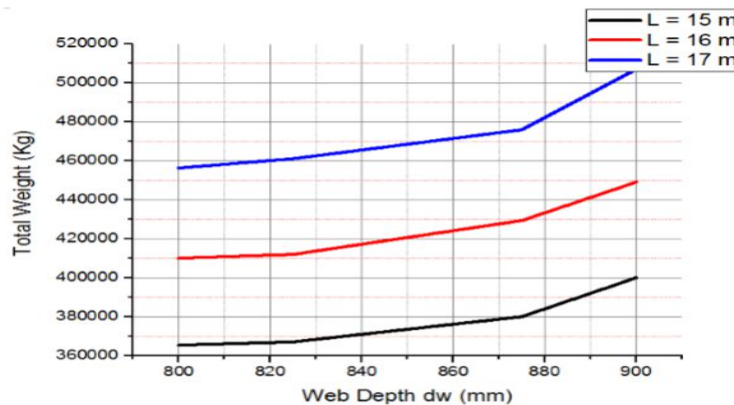
**Figure 9** Relationship between span-lengths and the total weight



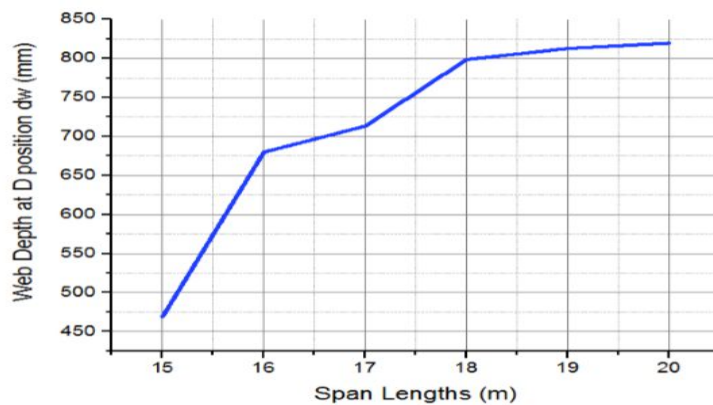
**Figure 10** Relationship between total imposed load and the total weight

According to Faluyi et al [15], the depth of a girder is often limited in industries due to headroom constraints and house service requirements. Therefore, the depth of the girder was examined in this study. It was increased in increments of 20 mm in mid span regions where the bending moment is maximum (position D). This was applicable for three different span lengths in order to evaluate the effect of changing web depths on the minimum weight design of the continuous plate girder. The results shown in figure 11 revealed that the total weight of the girder remains almost constant initially for a web depth ranged from 800 to 830 mm and

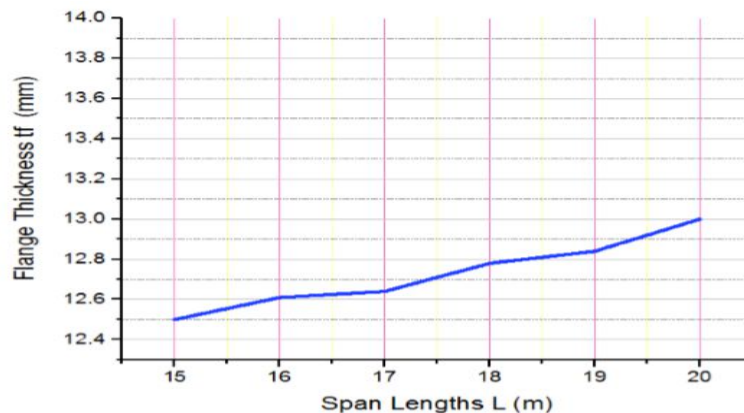
increases gradually for web depth ranged from 830 mm to 875 mm approximately, whereas a rapid growth of the minimum weight was noticed suddenly for web depth upper than 875 mm. This was observed in all the three span lengths. The results were predictable since it is reasonable to expect an increase in the depth of the plate girder, which would consequently increase the volume of the steel used and therefore a rise in the total steel weight. Thus, it is concluded that the thickness of the flange declines as the depth of the web rises in the aim to satisfy the need of the flange area constraint as the flange width rises. This means that an increase in web depth can produce an efficient and economic design.



**Figure 11** Relationship between the web depth and the total weight



**Figure 12** Relationship between span-lengths and depth of the web at position D



**Figure 13** Relationship between span-lengths and the flange thickness

Furthermore, it can be seen that as the web depth increases, it becomes more vulnerable to shear buckling. Consequently, it is necessary to increase the thickness of the web in order to satisfy the web buckling requirement. Moreover, the stiffener spacing has also contributed in the rapid increase of the total steel weight. It reduces to prevent the shear buckling failure of the web, which lead to increase the number of stiffeners required. Hence, it is concluded that the required weight of stiffeners offsets the benefit of having a deeper and a more slender web.

Moreover, it is revealed that the effect of varying span lengths on the changing rate of the total weight was noticeably small. This confirms the importance of satisfying the constraint requirement of the web shear buckling in design. It is shown that for a span length of 15 m, the web depth could not surpass 900 mm as after this point it is no longer satisfying the span to web depth ratio constraint, whereas for a span of 17 m, the web depth could not fall below 800 mm otherwise it violates the span to web depth constraint.

On closer inspection of the results shown in figure 12 and in consistency with what we learned in literature review, it can be clearly seen that by increasing the span length, the depth of the web also increases in order to satisfy the upper limit constraint of the span to depth ratio. Furthermore, this has opposing effects on the flange width so to satisfy the constraint of the web depth to flange width ratio, the flange width must be increased. Moreover, the increase in the dimensions of both depth and width provides a need to proportionally rise the thickness of these dimensions, therefore, leads to an overall rise in the weight of the structure. Additionally, a deep girder can become more vulnerable to shear buckling. Therefore, more stiffeners can be required in order to satisfy the minimum buckling requirements that also lead to increase the total weight of the continuous plate girder.

The values presented in figure 13 show that by increasing the span lengths, the flange thicknesses also increase which is justified in regard to the basics of strength of materials. This explains that having a larger span requires higher second moment of inertia and that the flange dimensions has a substantial role in girders moment capacity. Interestingly, the outcomes have not shown any decrease in the flange widths.

#### 4. DISCUSSION

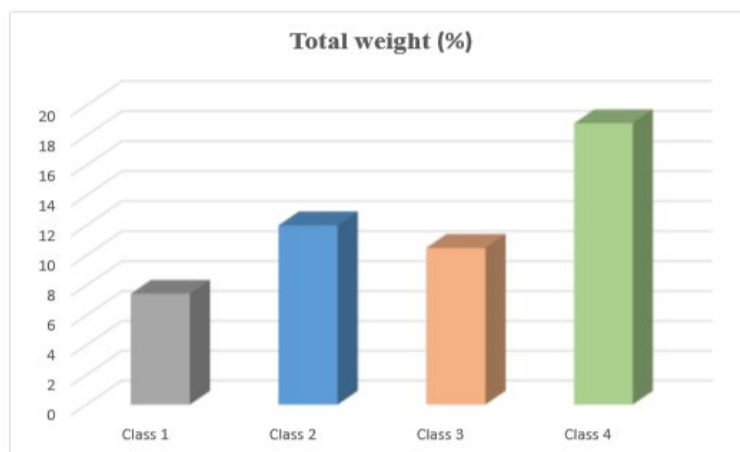
Continuous plate girders have been proved to be very effective in both buildings and bridges designs. This is due to their capability to resist to bending and shear forces at all sections all over their length. In structures, continuous spans are continuous over multiple supports, they are considered to be statically indeterminate, which make them beneficial in case uneven settlement of supports did not take place. Hence, continuous plate girders are favoured for greater span lengths. Many studies have been previously performed regarding continuous plate girders such as [1] that investigated the optimum design of welded steel plate girder using genetic algorithms with respect to minimum weight. Furthermore, many investigations have been carried out regarding the optimisation of simply supported girders namely prismatic and non-prismatic girders such as hunched, tapered and other irregular shapes. For instance,[15] has studied the optimum design of a simply supported plate girder using generalized reduced gradient and constrained artificial bee colony algorithms with respect to minimum weight. Additionally, [3] investigated the optimum design of a simply supported welded plate girder with tapered web with respect to minimum weight. However, little is known regarding continuous tapered plate girders in buildings which might be related to several reasons such as their high cost. Thus, our study will contribute significantly to the understanding of the effect of continuous tapered plate girders on their capacity and optimum weight.

Interestingly, [1] that investigated the optimum design of continuous welded plate girder (prismatic) using genetic algorithms with respect to minimum weight, according to IS 800:2007 Indian code, revealed that that the optimized weights of the plate girder attained through GA technique were significantly less in comparison to those assessed using conventional design. A maximum of 10.5 % and a minimum of 8.5 % reduction in weight of plate girder were encountered through using GA design. Furthermore,[15] that studied the optimum design of a simply supported plate girder using GRG solver algorithm and ABC evolutionary algorithm with respect to minimum weight and with accordance to BS 5950-1:2000 code, the study found that parametric optimization lead to significant decrease in weight of the simply supported girder. In particular, the GRG algorithm that yielded a 7.44% decrease in the girder cross sectional area compared to the conventional design, whereas ABC algorithm enabled a 7.25% decrease in the area.

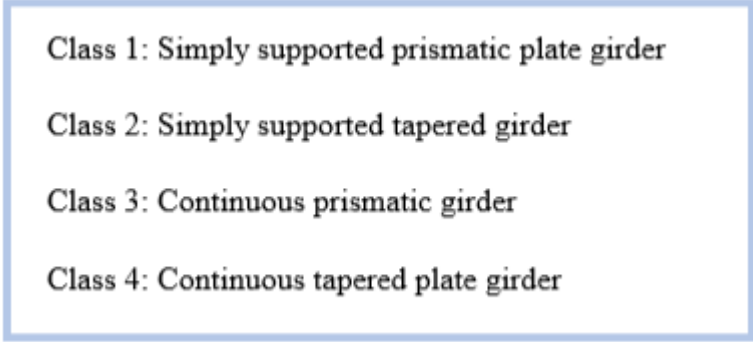
Moreover, [3] investigated the optimum design of a simply supported welded plate girder with tapered web with respect to minimum weight, according to IS 800:2007 Indian standards. The research also determined the buckling strength and the economy of the simply supported plate girder with tapered web. Therefore, three different cases have been examined using ANSYS. The results found were later compared with a prismatic plate girder. The study concluded that tapering the web lead to 12% reduction in weight of the girder. Hence, [3] concluded that tapering of web is considerably economical in weight. However, it does not show significant variation in the buckling resistance.

Additionally, another study conducted by our colleague [16] regarding the optimisation of steel plate girders in accordance with BS EN 1993-1-5 (Eurocode 3). This work revealed that deeper webs are more economical in minimum weight design. However, no minimum weight percentage was estimated in this study.

Furthermore, other study performed by another colleague [17] concerning the optimisation of plate girders with respect to minimum weight, in accordance with AISC 360:05 American standards, investigated the optimum design of prismatic and linear non-prismatic girders for different span live loads and span-lengths. [17] concluded that nonprismatic plate girders are more favourable in terms of weight with a reduction of 15.77% compared to their peer prismatic girders.



**Figure 14** Weight comparison for the case study

- 
- Class 1: Simply supported prismatic plate girder
  - Class 2: Simply supported tapered girder
  - Class 3: Continuous prismatic girder
  - Class 4: Continuous tapered plate girder

**Figure 15** Classification of results

In the present study, several parameters were investigated including the variation of web depths, the thickness and the width of flanges, the thickness of webs, the effect of changing both span-lengths and imposed loads in order to investigate their effect on the capacity of the continuous plate girder and its optimum weight. Moreover, a depth variation analysis was also studied to investigate how the overall weight of the continuous plate girder will be affected by an increase in the web depths. The results from the weight optimisation revealed that an increase in the web depth affected positively the reduction in the total weight. It affected the objective functions (minimum weight). This explains that selection of the girder geometry is independent of weight. The steel weight is a function of the total volume of the continuous plate girder. This volume relies upon the cross-sectional area and the span-length of the girder that have to satisfy both behavioural and side constraints. The weight of steel is always the minimum weight as the minimum area of steel was provided through weight optimisation in the work.

Additionally, our findings revealed that the optimisation of the continuous tapered plate girder lead to more economical design in terms of weight compared to all the optimisations of the previous simply supported and continuous prismatic girder investigations. The present study noticed a significant reduction of 18.81%, which is clearly shown below in figures 14, 15. It resulted in a structurally effective and economic design owing to its resistance capacity to reduce the net bending moment. In a continuous girder, large mid-span moments are decreased due to negative end moments. Hence, the design of the maximum bending moment value would ultimately be less significant in continuous girders, and requires smaller cross-section areas compared to a simply supported span. Therefore, in particular section, the capacity to withstand loads is considerably larger for a continuous girder. Furthermore, by tapering the continuous plate girder along its length, the bending resistance of the girder can be made to follow closely the bending moment diagram shape. For the aim of saving steel weight, the depth of the girders was reduced at the ends of the continuous plate girder in this study. This depended on the required shear resistance. Consequently, continuous tapered plate girders can be an efficient alternative in terms of both resistance capacity and can be highly effective in highly serviced buildings.

## 5. CONCLUSION

This work has presented an extensive study on optimum design regarding continuous plate girders with variable depths with respect to minimum weight, using GRG optimisation method embedded in Excel solver add-in. The primary purpose of the study is to demonstrate the benefits of using algorithms search into real-world problems. In particular, a case study was selected from the steel construction institution with slight modifications in order to implement the formulated framework design as an optimisation problem for the design of



continuous plate girders. This work achieved an economical design for continuous plate girder through optimum solution that minimise the weight and satisfy all constraints set. Moreover, the influence of various depths, span-lengths and girder weights on the design results was also investigated. In this work only I-section girders made from S355 steel were considered, supposing that elastic moment capacity was used. The main findings of this study can be summarised as follows:

- This study demonstrated how parametric optimisation of a continuous plate girder section could lead to significant reduction in weight. In particular, the generalised reduced gradient algorithm (GRG) yielded a 18.81% reduction in the total cross-sectional area of the continuous tapered plate girder.
- The optimisation of continuous plate girders designs are more economical than the conventional design implemented in the original design for the case study. The benefit in terms of weight is 18.81% reduction in comparison with conventional solutions.
- The initial optimisation revealed that the constraints of torsion, shear and stiffener buckling were all binding which demonstrates the buckling resistance to be the governing constraint that produces the optimum size of the girder.
- By tapering the continuous plate girder along its length, the bending resistance of the girder can be made to follow closely the bending moment diagram shape.
- Increase in web plate depth translates to reduction in the girder cross sectional area, and by inference decrease in the girder weight. This indicates that deep girders are more economical and can be effectively used over intermediate supports (tapered girders) in order to save weight in midspan regions. However, because of headroom constraint and web buckling susceptibility, the girder depth cannot be increased infinitely.
- The study revealed that the total weight of the girder cannot be decreased infinitely with a decrease in loading because of the inability of the girder dimensions to decrease while satisfying the girder sizing constraints.
- Continuous tapered plate girders can be an efficient alternative in terms of both resistance capacity and can be highly effective in highly serviced buildings.
- Tapered (varying depth) web is one of the new technique proposed in design in order to achieve economy and to reduce its self-weight.
- This study revealed the capability of GRG method to find out the optimum weight of the continuous plate girder through reducing the design variables as much as possible, considering the required strength of the plate girders to be able of safely resisting applied loads. Thus, this method succeeded to acquire continuous plate girders with minimum weight and can be deduced that optimisation is a powerful technique.

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